

RAP CRADA REPORT

Jacques Millaud

JEMillaud@lbl.gov

To:(510) 486 4169, Fax:(510) 486 7557

Measurement Science Group

Engineering Division

Lawrence Berkeley National Laboratory

Purpose of this document:

The intent of this report is to better define the frame of the co-development by Bruker-AXS and Lawrence Berkeley National Laboratory (LBNL) of high event rate, high spatial resolution X-ray detectors systems based on PPAC detectors.

High event rate means no less than an order of magnitude above current delay lines based readout systems. These systems typically deliver event rates of 10^6 events/s over the entire detector area. This development targets spatial resolution of 100 microns or better.

The approach retained is to use highly segmented collection electrodes and to avoid data capture and processing bottlenecks associated with single point data flows. Parallelism in data handling is essential. The technical challenge is to maximize the event rate for the entire detector while maintaining a spatial resolution of 100 microns or better. The design challenge is to keep the cost of the instrument low enough to ensure economic viability and competitiveness.

- Funding background:**

Bruker-AXS and LBNL jointly responded to two calls for proposals by the Department of Energy (DOE). Short term and limited funding was granted by DOE with a matching contribution from Bruker-AXS for a total of about \$110,000. The target of this development is to determine an “optimum” implementation of a detector system. The second proposal for a total of about \$550,000 was rejected. It is the intent of both parties to submit an updated and upgraded proposal to DOE or other federal agencies during the upcoming fiscal year.

- **Technical background:**

Each time a X-ray is absorbed in the gas detector an avalanche is triggered and a cloud of electrons drifts towards a resistive electrode. Signals induced on a segmented electrode are processed individually and in parallel to a certain point. The data (signal amplitude) collected on a set of neighbouring electrodes is used to determine the centroid of the electron cloud. Extracting additional information such as the total energy deposited by the incoming photon or the time of occurrence is feasible from the measurements but is not part of the current development.

The PPAC gas detector consist of a X-ray conversion area, a drift area, a gas amplification area and the signal collection structures. The detector will operate at gains of the order of 10^5 . It is estimated that the gain is sufficiently low that there is no dead time per say associated with each event. Rather the pile up of events will, in all likelihood, result in subsequent events yielding a lesser amount of charge.

The collecting electrode plane can be segmented using pixels or orthogonal strips. The segmentation pitch is such that 3 to possibly 7 electrodes “cover” the electron cloud. Using a higher number of segments will yield higher spatial resolution. Work being conducted at Bruker-AXS will determine what the dimension of the cloud will be. It must be noted that the cloud dimension will increase from the center of the detector to the periphery. This variation of the cloud dimension, hence of the number of electrons collected per electrode, forbids the implementation of a hardwired data acquisition whereas the recognition of a cluster of electrodes is pre-determined. An example of such hard wiring would be to impose the recognition of a cluster of 3 strips. A contrario leaving flexibility for the recognition of clusters impose that the signals delivered by all electrodes be captured when an event occurs.

- **Pixels or orthogonal strips:**

The choice between pixels and strips rest on trade offs between speed, simplicity and costs. For a given extent of the electron cloud, the area covered by pixels is substantially less than for strips. The electronic dead time associated with the processing of the signals from pixels applies to a small area of the detector. As an example if a cloud covers a 3x3 cluster of pixels it will also cover 3 strips in the X direction and 3 strips in the Y direction. If pixels are at a 1mm pitch and a strip is 10cm long at the same pitch then the electronic dead time for the strips is associated to an area ($2 \times 300 \cdot 9$) mm² versus 9mm² for the pixels. In principle the inverse ratio of the area determines the ratio in event rate. In practical term the data collection architecture cannot collect all channels at the maximum rate thus limiting the event rate. Ultimately the level of parallelism in the data collection architecture and the level of buffering determines how fast a pixel based system will operate. It is reasonable to expect that such systems will operate at 5 to 10 times the rate of long strips based systems. Pixels will perform particularly well when local event rates are high and global rates are average.

Strip based systems require a time correlation (coincidence) between the two projections. Multiple events during the coincidence time cannot be unfolded (I.e. [X_i,X_j],[Y_k,Y_l]). There is no information to determine how X_s and Y_s should be associated. Nonetheless strips have some advantages. The number of electronics channels is smaller as it varies linearly with the detector linear dimension rather than with its area. One would expect electronic costs to be lower. At narrow pitches (I.e. 200 microns) pixels require a more complex data collection architecture and a more complex packaging particularly at the boundary of areas instrumented by different processing units (ASICs).

- **Signals/timing/event rates:**

At the detector:

The PPAC is an avalanche gas detector. The avalanche is localised in an area of a few hundred microns in diameter. It last of the order of 15 nanoseconds (ns). The total number of electrons in the cloud is typically of the order of 10^7 electrons at gas gains of 10^5 . Event rates of $10^5/\text{mm}^2/\text{s}$ at 5% to 10% losses level are feasible. The transverse extent of the cloud is associated with the thermal diffusion of the electrons in the conversion/drift area(s) and in the amplification gap. At the end of maximizing the event rate and the spatial resolution Bruker-AXS will work on ways to reduce the dimension of the cloud. Current numbers for the distribution in the cloud are .5mm to 1mm rms. It must be noted that an induced signal of the opposite polarity appears at the periphery of the cloud. These signals will impact the response of neighbouring electrodes hence increase the apparent extent of the cloud. They might also be usable to enhance the spatial resolution.

At the analog electronics output:

As indicated hereabove the signal induced on the collecting electrodes last about 15ms. The analog processing chain consist of an integrator and a shaper. The signal peaks at 1.5ns and has a baseline width of 50ns. The signals collected on the segmented electrodes are used to determine the center of the charge in the cloud, the impact point of the photon. Accepting event pile ups, even limited, would deteriorate the spatial resolution hence the baseline width of the signal should be considered “dead” time when considering events losses. It must be recognized that under conditions of limited signals pile up it may be possible to maintain a spatial resolution of 100 microns.

A design targeting 8 cm strips (8pF capacitance) has been completed and simulated. Simulation shows noise levels of 600 electrons rms. Including the contribution of neighbouring strips 03/13/2002

A noise budget of a 1000 electrons should be considered. The additional noise is associated with the interstrip capacitance. The strip's signal to noise ratio remains of the order of 100 and is consistent with the overall accuracy needed for the determination of the center of the charge cloud. Shorter strips and pixels will have less capacitance hence the processing electronics will display less noise. It is also possible to reduce the baseline width but this has little interest for pixels and short strips.

At the digitization level:

If each strip (column) is instrumented with its own analog to digital converter (ADC), the “dead” time associated with digitization is also of the order of 50ns. Faster ADCs are commercially available at some extra cost and power. Sharing ADCs between channels does not appear to save much as the high speed routing of analog signals prior to digitization will induce additional dead time, power and circuitry.

At the data collection level:

There are several scenario in regard to data collection. Assuming an average event rate of 5×10^6 /area/s, it is always possible to provide a multi-cell storage of the incoming data. Such a storage will de-randomize the incoming data. If storage is deep enough, it will suffice that the data be readout of the storage at a rate faster than the average time between events: 200ns under the current assumption.

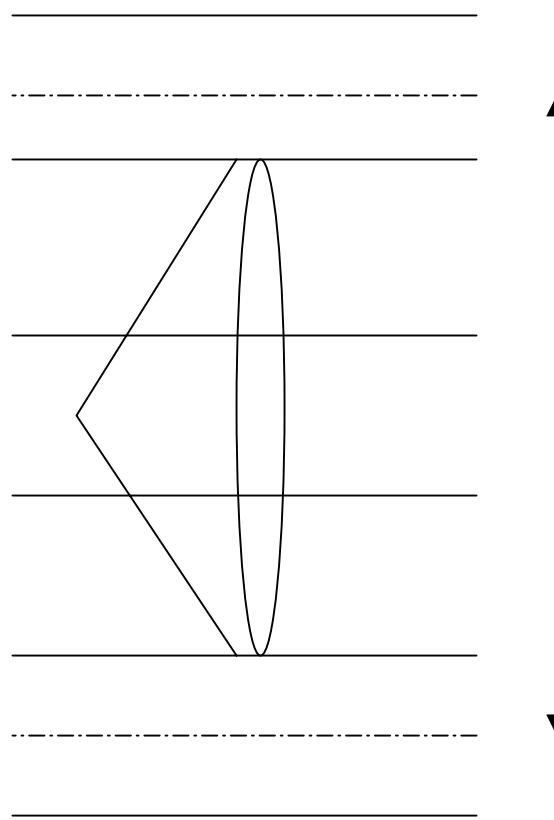
At the data processing level:

It must be verified if the simplest level of data processing can be performed during the mean time between events. Such processing could be the rejection of ambiguous events and the storage of data in the computer. A more advanced capability would extract the coordinates of the center of the cloud.

- Sustainable event rates per strip:

Sustainable rates are estimated for the simpler case of orthogonal strips. Event rates achievable using a pixel segmentation are highly dependant on the architecture of the capture and readout electronic hence it is quite difficult to derive realistic figures without referring to a specific implementation.

Assuming a dead time of 50ns for the entire data capture process it is possible to derive sustainable event rates. One must differentiate between the data rate and the event rate on a strip. The electron cloud extend over several contiguous strips hence a strip will capture some of the electrons even though the event is centered on a neighbouring strip.



Events occurring in the area between the arrows will induce a signal on the central strip.

It is clear that if electron clouds extend over N strips, the rate on a strip is the sum of the event rates on the strip itself, on the $(N-1)/2$ strips on each side plus the rate on the half of each strip immediately outside the cluster. Assuming a uniform flood field the data rate will be 4 times a strip event rate for clouds extending on 3 strips and and 6 times if the cluster is 5 strips wide. Obviously event losses are derived from the relative magnitude of the dead time and the data rate. The table hereunder summarizes losses at various data rates. A uniform flood field and a 50ns “dead” time are assumed. It is also assumed that if two events occur on a strip within the “dead” time both events are lost.

Data rate	Event rate (3 strips)	Event rate (5 strips)	Losses (%)
2×10^6	5×10^6	333×10^6	9.5
1×10^6	25×10^6	166×10^6	4.88
$.510^6$	$.125 \times 10^6$	$.08333 \times 10^6$	2.46

Losses on a strip will vary with the diffraction pattern. If the width of the diffraction rings is about the same as of a strip then the data rate and the event rate can be very close as neighbouring strips contribute relatively little data. It is possible to conclude that at event losses of 5% sustainable event rates per strip of 250,000events/s are possible.

These estimates do not take in account the physical dimensions - length and pitch - of the strips. As a numerical example, assuming a cloud extent of 3mm, a strip length of 7cm and strip pitch of 1mm, event rates between 10 and 20×10^6 /s may be feasible over a 7x7cm quadrant. Tiles of shorter strips would yield higher rates over the same area.

• Development roadmap:

During discussions at Bruker-AXS on June 12 2001, LBNL suggested an implementation using short strips. A detector system could be built using tiles made of 32 strips in each direction. At a pitch of 1mm the tile would cover 32x32mm. Assuming conservatively (see estimates in the previous section) a 5×10^6 events/s per tile the rate over a 7x7cm area would be about 24×10^6 events/s. A pitch of 200 microns would yield a 25 times higher rate. Again the pitch will be determined by the cloud extent.

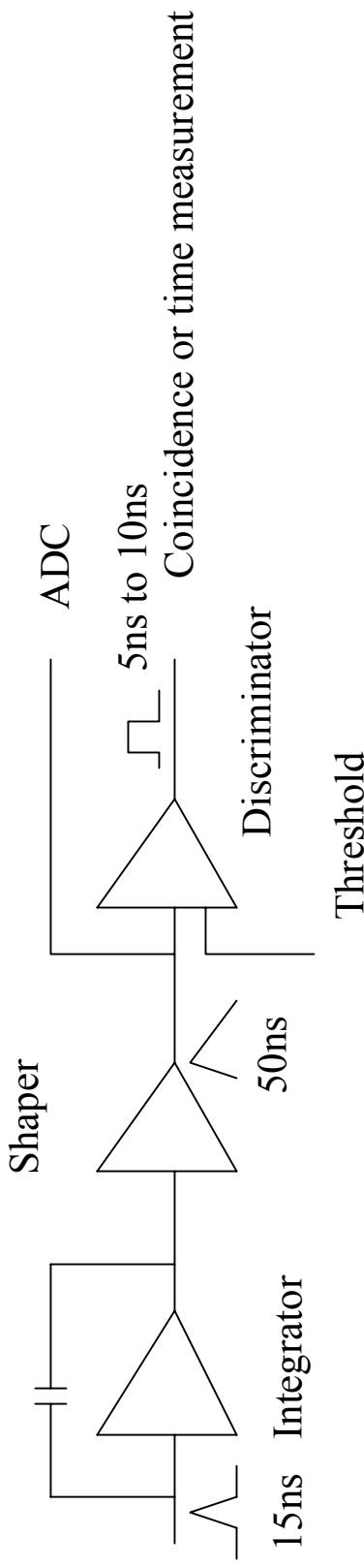
Using the concept of short strips tiles, the number of channels that need to be instrumented is about 350 for a 7x7cm quadrant. An entire detector will require 1400 channels. If we assume that 64 front end channels can be implemented in an ASIC, over 25 ASICs would be needed to instrument the detector. The prototyping of ASICs through MOSIS delivers 25 parts total although a few additional parts can be bought. Still taking in account the parts needed for the characterization of the ASIC plus the production yield it does not appear that a prototyping batch will be sufficient to build a full scale detector prototype.

Bruker-AXS suggested that taking in account the limited funding available and as an intermediary step in the development of higher event rates detectors one could target a four quadrant detector. Each 7x7cm quadrant would use long strips at a mm pitch. The total number of channels would be 560 and could be instrumented using the ASIC described earlier. Event rates of 50×10^6 /s should be feasible at moderate losses, making this intermediary detector a competitive product on the market. Additional funding will be needed to complete such a detector to support ASIC and system design. Based on the previous estimates faster detector systems could be built funding permitting.

It was decided to proceed along these lines and to develop the implementation concepts for this intermediary detector.

- Design implementation:

For the intermediary detector we consider two possible approaches. They share a common implementation of the analog front end and discriminator.



The discriminator could be zero crossing or constant fraction although a simple discriminator may suffice. Taking in account that the amplifier noise is low (of the order of a 1000e⁻), that the minimal signal is high (of the order of 50,000e⁻) and that the rise time is about 10ns, the time walk or time resolution could be of the order of 2ms. This assumes using a 10,000e⁻ discriminator threshold on signals ranging between a 50,000e⁻ signal and a 500,000e⁻ signal. The discriminator pulse width could be between 5ns and 10ns.

1- “Brute force” approach:

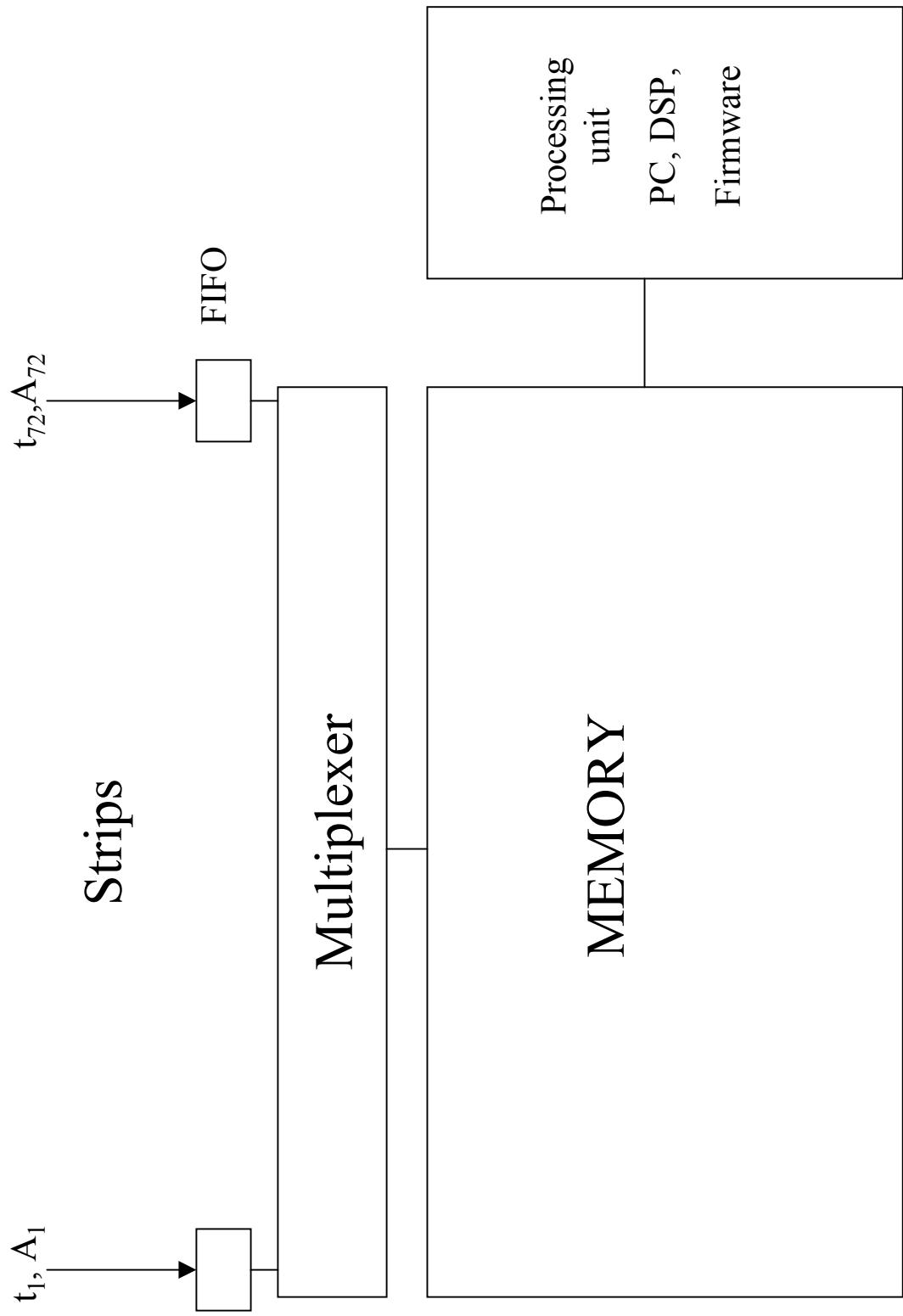
Each strip delivers the following information consisting of an address (Addr_i), a time of occurrence (t_i) and an amplitude (A_i). Each strip is individually stored in a large memory I.e. capable of storing 10^6 events. The temporal and spatial correlation required to recognize a cluster, the filtering of events (the rejection of multiples), the correlation between the X and Y projections are performed off line using a PC, or using a DSP (or any firmware) or using both. The number of events to be stored multiplied by the average number of strips per cluster defines the number of words in the memory.

With this approach the information is minimally filtered as all recordable data is kept for further processing. The strip information has the following structure:

- Addr_i : 6 to 7 bits
- A_i : 8 bits
- T_{iV} : 5 bits time vernier
- T_{iC} : 4 to 8 bits time reference coarse

The memory field for one projection (X or Y) would be 32 bits maximum. Each projection has its own memory. Typically a $8 \cdot 10^6$ words 32 bit memory will be needed for each projection.

The time measurement will be done using a reference clock. Using a 32 ns clock period the time vernier would provide a resolution of about 1ns. The number of bits needed for the coarse clock measurement varies with the event rate. The limited number of bits allocated for the coarse clock should not result in errors in the cluster recognition as events would appear in the memory at no less than 500ns intervals and up to 8 microseconds in the memory storage.
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Brute force approach: Each triggering strip stores its A_i , t_{iv} , t_{ic} data in a shallow depth FIFO. The data is then multiplexed on to the main memory. The role of the FIFO is to derandomize the incoming data. The strip address is generated at the level of the multiplexer.

The FIFO depth is determined by the rate of recurrence on a strip, the “dead” time of a strip (50ns) and the mean time to store a cluster in the main memory. Standard devices have a minimum depth of 16 which is far more than needed. It may be feasible to design a simpler storage in a programmable device. The data provided by the FIFOs is fed to the main memory. The order of entry may not conserve spatial or even temporal continuity. As indicated earlier using the 4 to 8 bits of the coarse time measurement, time re-correlation can be performed.

The main memory can be built from SRAM, Dual port SRAM, FIFOs depending on the target selected for processing the data. With current technology event rates as high as 10MHz may be feasible. This is equivalent to a word rate of 50MHz assuming average 5 strips clusters.

The overall rate can be increased substantially by segmenting the storage. For example 4 sections of 18 strips each could be used. The peak rate could be close to 4 times higher. This increases only minimally the hardware if the total number of events remain the same.

2- Storage triggered by the {X}, {Y} coincidence:

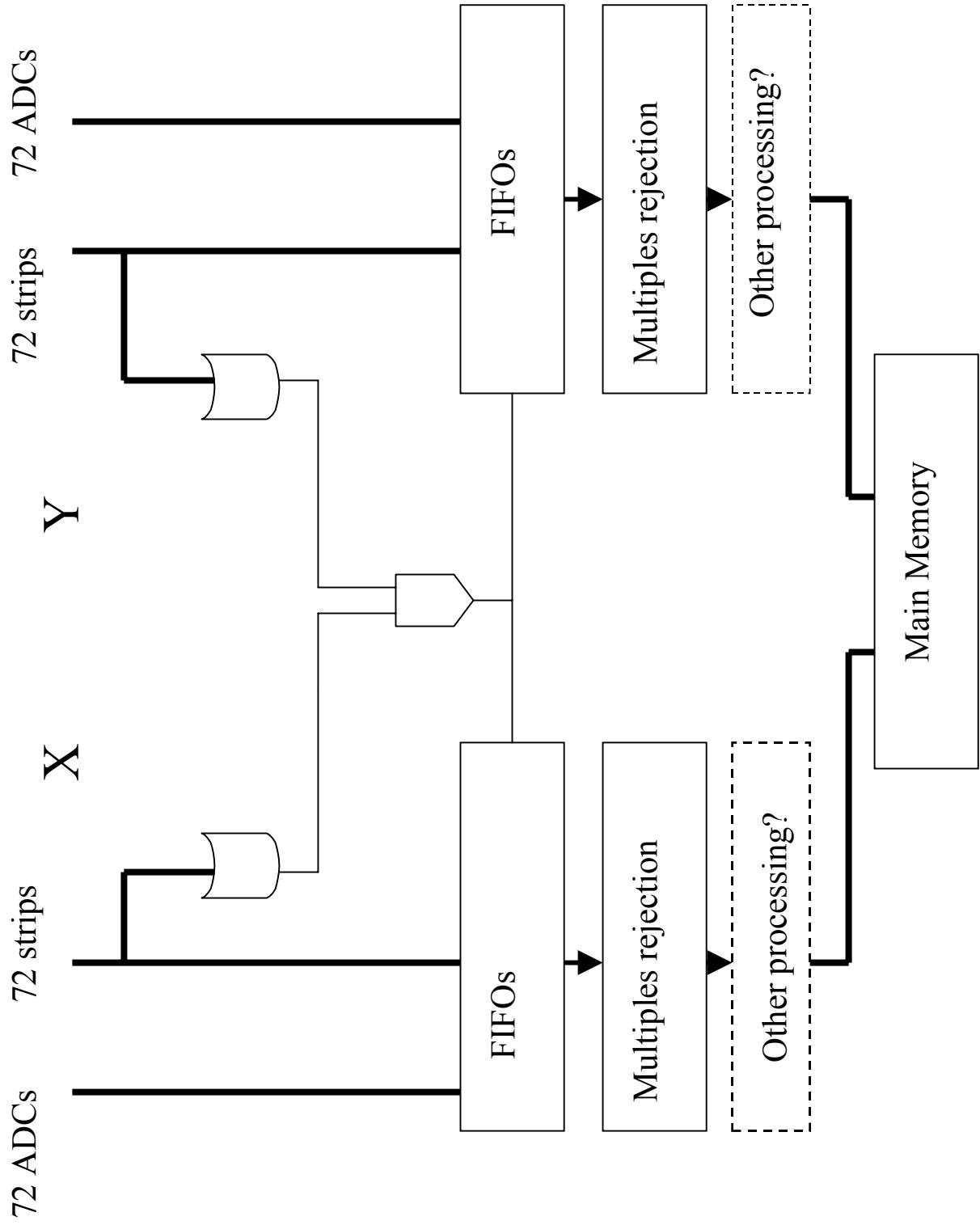
All strips on a projection are Ored together and in coincidence with the OR of the other projection. The coincidence signal records the strips' pattern and each strip's amplitude measurement into storage. There is no direct recording of time for individual strips although the time of the coincidence could be recorded for time resolved applications. The data is recorded first in a FIFO. When readingout data from the FIFO multiples are rejected then the X and Y data is stored in an event memory. Fast DSPs and firmware can be used to reduce the event data to a X and Y location, optionally an amplitude and a time. Processing can also be done off line. Assuming an event rate of 5×10^6 /s the losses associated with the probability of 2 events during the time of coincidence are:

Discriminator shaping/dead time:	5ns	10ns	20ns
Losses in %:	2.46	4.9	9.5

These figures have been derived by recognizing that if two events occur during the dead time both are lost. The latter one does not generate a coincidence (dead time), the first one records two locations in X and two in Y that cannot be correlated. At 10^7 events/s losses essentially double.

The amount of hardware to be build is comparable to the brute force approach although the absence of time measurement for each strip is a simplification. Data is somewhat filtered by the coincidence.

Segmentation in a 2x2 or 4x4 matrix of coincidences will increase the data rate but at some increase in complexity as each ADC data has to be stored in 4 differents units of storage.



- **Summary:**

There are two possibilities of recording data at typical event rates of without substantial event losses (~5%). There are several ways to increase the event rate by segmenting the data acquisition system. For reasons of simplicity, time, budget using a single coincidence appears a better choice. It must be remembered that 5×10^6 events/s for each quadrant yields about 2×10^7 events/s on the entire detector. This is more than an order of magnitude higher than current detector systems.

- **Status of the ASIC development:**

LBNL has advanced the design of a test ASIC. This ASIC contains individual functions of the analogue front end as well as 16 full analog channels (no discriminator). Beyond the characterization of the analog function(s) this device can be used to instrument a small area (I.e. 1x1 cm) of a PPAC as per the statement of work. It may also be used to instrument a larger area (a quadrant) if the yield is high enough to provide a sufficient number of devices. The device has been tested and largely meets specifications although there is a wider spread than expected in channel gain and in the output DC offset.